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GEOSYNCHRONOUS ORBIT DETERMINATION USING HIGH ACCURACY ANGULAR OBSERVATIONS

Benjamin Visser[*], Chris Sabol[†], Scott Dahlke[‡]

As part of the High Accuracy Network Determination System (HANDS), Raven-class telescopes were built to provide observations with less than an arcsecond of error. While achieving low noise levels, previous work has shown that HANDS optical data contain systematic errors which limit orbit determination accuracy; therefore, the challenge is being able to fully utilize that data to produce deep-space orbits with great certainty. This paper presents findings that better define the limitations of the angles-only observation sets. The results presented supplement, refine, and provide more detailed analysis of the previous work in the areas of systematic error modeling, error assessment, and unmodeled perturbations. This research was accomplished by analyzing orbit determination solutions for a geosynchronous satellite (TDRS-5) and a decommissioned supersynchronous defense satellite (DSCS-3/A1).

INTRODUCTION

The High Accuracy Network Determination System (HANDS) is a research and development program of the Air Force Maui Optical and Supercomputing site (AMOS) that incorporates inexpensive, rapidly deployable, autonomous Raven-class telescope systems and state of the art data processing and exploitation algorithms to provide space surveillance information. The first HANDS demonstration was to provide high accuracy angular observations of deep-space satellites to supplement the Air Force Satellite Control Network (AFSCN) in determining orbits.[1]

Simulation studies have shown that if AFSCN ranging observations are supplemented by high accuracy angular observations, the resulting orbits improve dramatically compared to the range-based solutions alone. Even if observation biases were present in the angular data and were estimated as part of the orbit determination process, orbits accurate to the 100 m level could be generated.[2] However, if the angular data were unbiased or well-calibrated, the orbit error could drop to the 10 m level.[3]

HANDS utilizes Raven-class sensors to provide right ascension and declination measurements with less than one arcsecond of error.[4,5] The key to Raven's accuracy is the use of astrometry: right ascension and declination metrics are generated by comparing

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the observed location of the satellite to the known location of background stars in a CCD image. Astrometry has been an R&D focus area at AMOS and is currently used for a variety of applications.[6] By using high accuracy star catalogs, one would expect high accuracy angular observations of satellites with little or no systematic error is possible.

While previous real data analysis has shown HANDS optical data to be very accurate and contain low noise levels, they have also shown that the data contained systematic errors.[1,5] By comparing the optical data to reference orbits, which are reported to be more accurate than the optical observation data, information regarding the errors in the optical observations has been obtained. The biases change day to day and in some cases, appear to follow a daily trend. These systematic errors do not preclude the determination of accurate orbits using HANDS data; however, if the simulation studies are correct, they do make the difference between the 100 m level orbits shown in previous work and the 10 m level orbits which may be possible.

The purpose of this paper is to supplement, refine, and provide more detailed analysis of the previous work in the areas of systematic error modeling, error assessment, and unmodeled perturbations. Several strategies are employed in an attempt to account for the systematic errors in the optical data. The impact of unmodeled accelerations on solution quality is analyzed. Finally, the use of consistency checks to infer orbit accuracy is reviewed.

APPROACH

This research was accomplished by analyzing orbit determination solutions for a geosynchronous satellite (TDRS-5) and a decommissioned supersynchronous defense satellite (DSCS-3/A1). Observations were provided by the HANDS Raven telescope located near sea level at the Remote Maui Experiment (RME) site in Kihei, Hawaii. Right ascension (RA) and declination (Dec) data were collected over 15 to 25 December 2003; the only night data was not collected during that span was on 20 December due to poor weather although there were shorter duration outages on other days as well. Additionally, no TDRS-5 data was collected on December 21. A typical tracking period covered 6 hours per night. In total, 1020 observation pairs of TDRS-5 and 2166 observation pairs of DSCS-3/A1 were collected.

In addition to the optical tracking data, osculating element sets for TDRS-5 were available from the Goddard Space Flight Center (GSFC).[7] These osculating elements were propagated with the Operational version of the Goddard Trajectory Determination System (Ops GTDS) between the period of 15 to 25 December 2003.[8] Even though it is known that those element sets may have tens of meters of error, this was used as the truth orbit for the TDRS-5 satellite.[1,9] Unfortunately, there was no external reference orbit available for DSCS-3/A1.

Two software suites were available for orbit determination and analysis: Ops GTDS and Special K.[8,10,11] Ops GTDS was the primary analysis package and has been used at

NASA since the early 1970's and at AFRL since 1997. Special K was provided by the Naval Research Laboratory to allow parallel special perturbations processing of the entire space catalog at the Maui High Performance Computing Center, but for this research it served more as a diagnostic utility to insure consistent results. Both of these systems use a weighted, batch-least-squares estimator. In order to stay consistent among all runs and different software, the following perturbation models were used:

- 8x8 JGM2 geopotential,
- point source sun and moon gravitational effects,
- solar radiation pressure with a spherical satellite model.

For DSCS-3/A1, Ops GTDS also estimated an along-track acceleration to account for small momentum upload maneuvers.

A significant amount of observation preprocessing occurred before differential corrections were performed. First, it has been observed that Ops GTDS has difficulty converging to a solution with RA & Dec only data and Special-K does not contain validated RA & Dec observation models. Therefore, the topocentric, J2000-based RA & Dec observation pairs were transformed into azimuth (Az) and elevation (el). However, previous work has shown that Ops GTDS does not properly account for the motion of the observer during the light transit time correction for Az & El data.[12] Thus, the light time correction was applied in the preprocessing and not in the differential correction.

Correcting for the time it takes light to reach the observation site from the geosynchronous (GEO) and supersynchronous orbits is necessary. For example, light takes 0.12 sec to travel 36,000 km. With GEO satellites moving at speeds of roughly 3 km/sec, this time amounts to approximately 300 m of error in the along-track direction and has some minor effects on the other residual components. Light time corrections for topocentric RA & Dec data simply consist of a time-tag change to the observation pairs. This change is simply the amount of time it takes for the light to leave the satellite and arrive at the ground observer. To model this, one has to have range knowledge. Rather than implement a propagator in the observation preprocessing software, a functional approximation was developed to describe the range. Actual range was calculated using Satellite Toolkit (STK) and two-line element sets (TLE's) for TDRS-5 and DSCS-3. Figure 1 is a graphical representation of the range model developed to approximate the satellites' positions and the range computed using Satellite Toolkit (STK) and the TLE's.

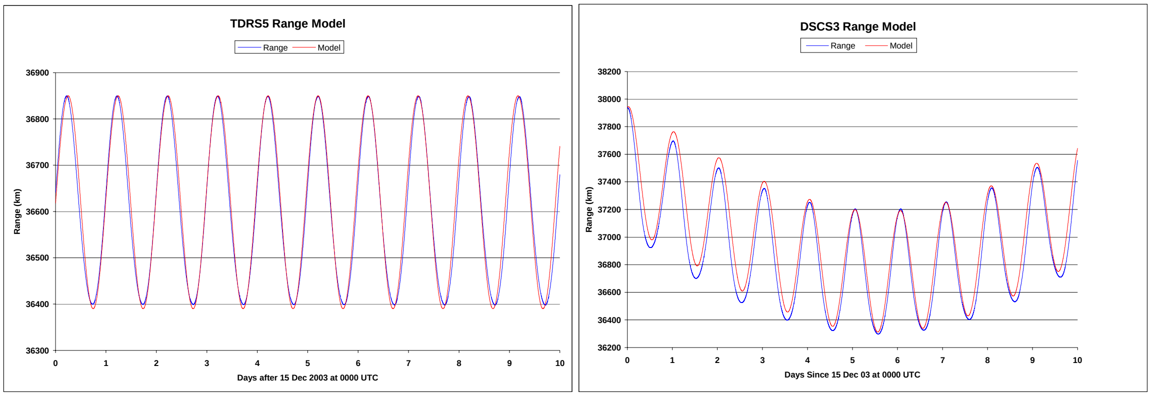

Figure 1 Derived Models for TDRS-5 and DSCS-3 Range, 15-25 Dec 2003

The next step in the observation preprocessing applied bias correction models to the data. In previous work, constant, daily biases were removed from the data. Table 1 summarizes the metric data mean differences and standard deviations during the observation period used in this study.[1] These values were generated by comparing the observations to reference orbits defined via daily osculating element sets from the Goddard Space Flight Center (GSFC) for TDRSS. These values are believed to be accurate to below 0.33 arcseconds.[1]

Table 1. Difference statistics between optical observations and GSFC reference orbit

Date	Satellite	RA Mean (arcsec)	RA Std Dev (arcsec)	DEC Mean (arcsec)	DEC Std Dev (arcsec)
12/15/2003	TDRS-5	0.36	0.76	1.01	0.33
12/16/2003	TDRS-5	0.27	1.03	0.69	0.46
12/17/2003	TDRS-5	0.18	0.91	1.25	0.42
12/18/2003	TDRS-5	0.02	0.99	1.80	0.33
12/19/2003	TDRS-5	0.03	1.03	0.88	0.49
12/21/2003	TDRS-8	-0.06	0.94	0.90	0.44
12/22/2003	TDRS-5	0.33	1.04	0.96	0.56
12/23/2003	TDRS-5	0.82	0.98	0.62	0.43
12/24/2003	TDRS-5	0.35	2.50	1.17	1.16

By examining measurement statistics over many more days than those presented in Table 1, it was previously found that observations of TDRS-5 and TDRS-8 have daily biases that are very similar.[1,5] It was therefore reasoned that one might be able to use TDRS-5 observations to calibrate the sensor each night. The principle assumption here was that the biases were not satellite dependant and that they might be roughly constant for each observation session. If this were true, this approach's accuracy would only be limited by the accuracy of the TDRSS orbits. Reference 5 appeared to have some success with this approach.

Previous work also showed that the constant, daily biases did not appear to provide adequate bias modeling.[1] Plots of the orbit difference from the reference orbit as a function of hour of day indicated a daily periodic error in RA. This periodic error was modeled and removed from the observations in the preprocessing. The orbit determination results for TDRS-5 in this case indicate the orbit accuracy achievable with properly calibrated angles-only data.

Once the observations were preprocessed, differential corrections were performed to analyze the impact of the various bias modeling techniques and also to assess the impact of unmodeled perturbations. The validity of the approaches were gauged on the resulting orbit determination error. Judging orbit determination error is a challenge in its own right. For TDRS-5, orbit error was determined by comparing the angles-only orbit solutions to the GSFC reference orbits. Since there was not a reference orbit available for DSCS-3 it was decided to check the quality of the orbits by an abutment check.

For the abutment check, a six day fit from 15-21 Dec and a five day fit from 19-24 Dec (there was no data on the 20th) were generated and then compared during the whole ten day period. Normally, it would be preferably to avoid comparing solutions with common observation data; however, since there was no optical tracking data available on the 20th, there was not sufficient tracking data available to generate two independent fits within the ten day tracking interval.

In addition to the comparisons to the reference orbit and abutment checks, two additional error analysis metrics were employed. First, solution standard deviations were reviewed as a relative indicator of quality. Second, observation residuals were inspected to determine how well the solutions fit the data. Reference 13 discusses some of the advantages and disadvantages of the error analysis approaches.

RESULTS

A previous study[1] had used a ten day fit span and the same TDRS-5 observation data for 15 Dec – 24 Dec 2003, with no data available on either the 20th or the 21st. The determined orbit was subsequently compared to the GFSC osculating element set reference orbit previously mentioned and the differences plotted. Figure 2 shows a similar plot found in this study in which none of the observation biases had been removed. In general, one can see 50 m periodic error in the radial direction, 100 m periodic error in the along-track direction with a 100 m offset and a slight positive increase, and 200 m periodic error in the cross-track direction. Note that the errors are minimal during the early part of the UTC day which corresponds to the tracking windows.

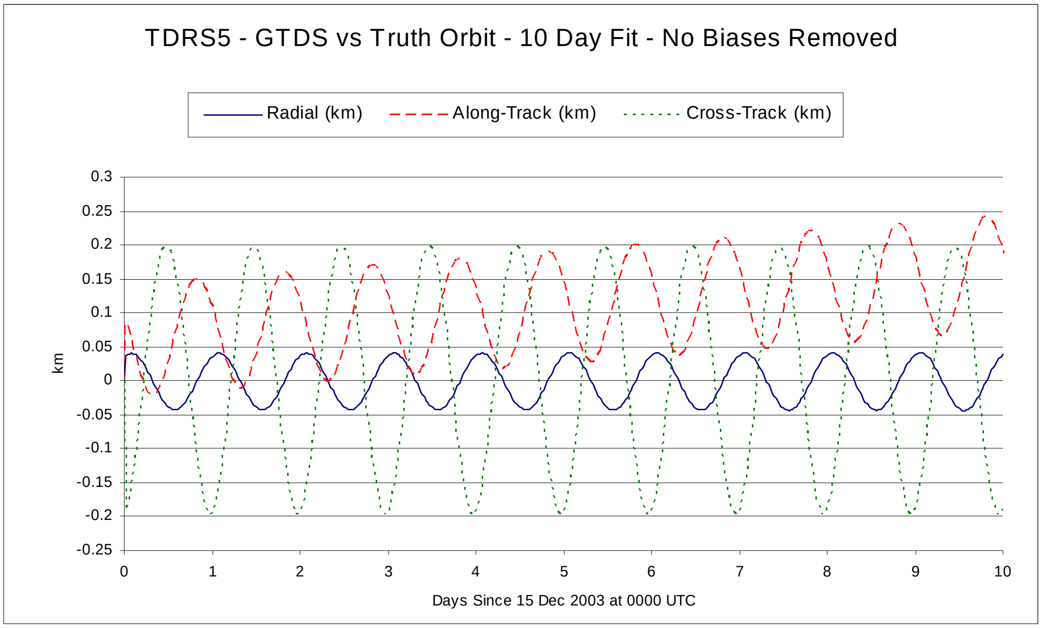

Figure 2 Ten Day Fit Compared to Reference Orbit

The next step the previous study looked at was what happened when the daily measurement errors, found in Table 1, were removed from the observation data. Figure 3 plots the resulting differences after this correction was made. One can see that now there is a 60 m periodic error in the radial direction, 200 m periodic error in the along-track direction following the same trends as before, but only a 10 m error in the cross-track direction.

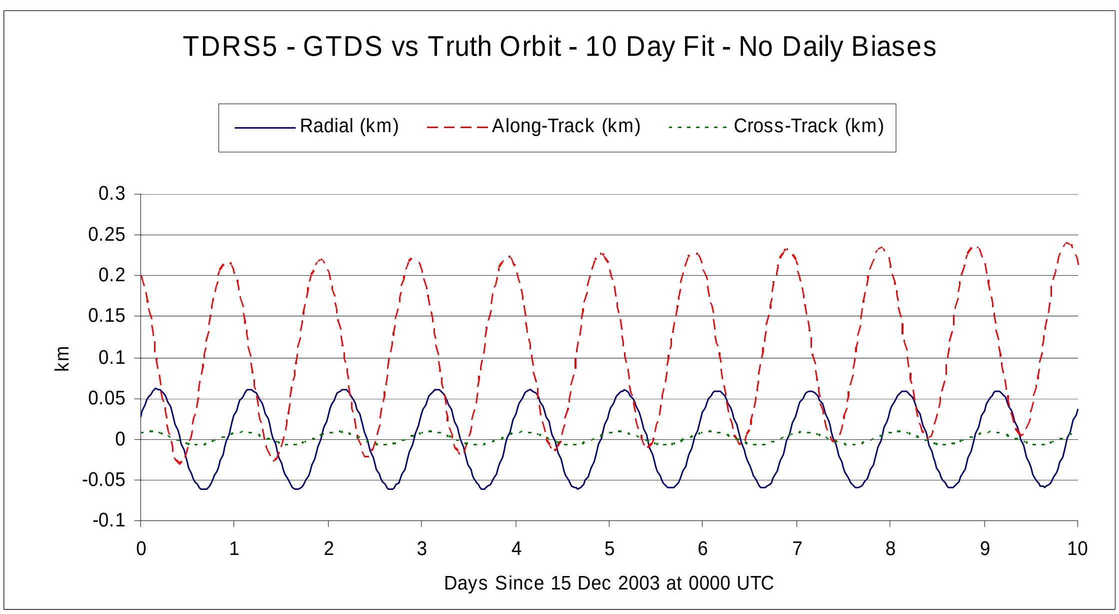

Figure 3 Ten Day Fit Compared to Reference Orbit

The previous work concluded by presenting a graph of right ascension differences from the reference orbit versus hour of the day and showed that there is also a daily periodic systematic error. It was hypothesized that if this error could be removed that the along-track differences of Fig. 3 may also be reduced to the 10 m level like the cross-track error had. By applying a fit to this data and removing the hourly dependent biases from the observation data the results in Figure 4 were obtained. These results show a less than 5 m period error in the radial direction, a periodic error of less than 10 m and a small drift in the along-track direction, and less than 10 m periodic error in the cross-track direction.

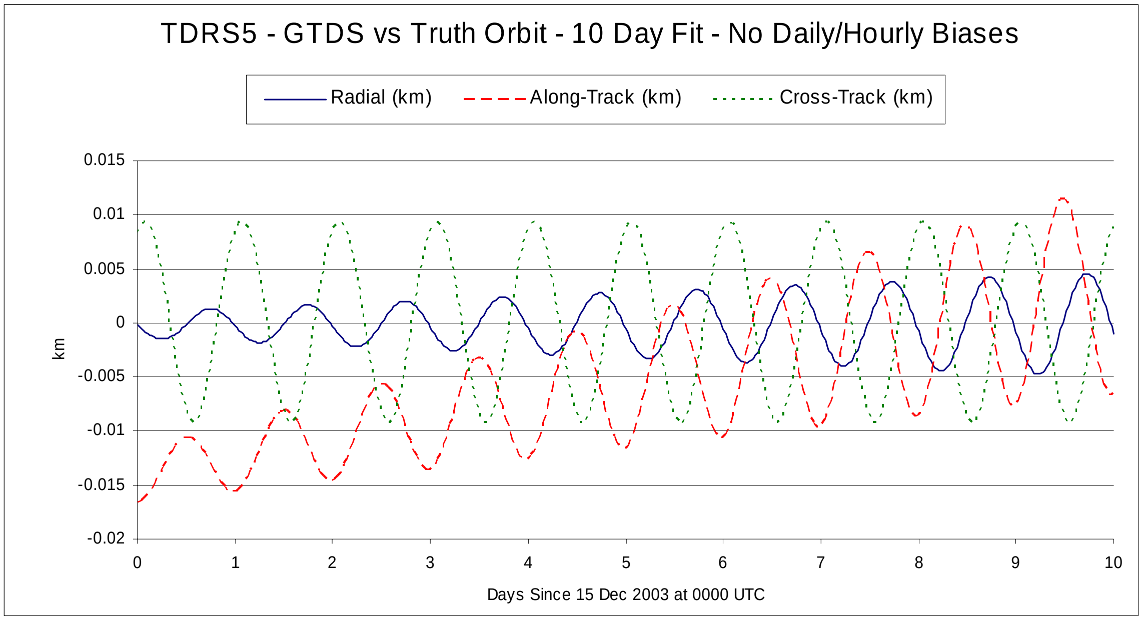

Figure 4 Ten Day Fit Compared to Reference Orbit

All of these results demonstrate that if the systematic errors in the optical data can be modeled, very accurate results may be obtained. The resulting residuals in Figure 4 are within the error bounds of the reference orbit. Therefore, the combination of very accurate HANDS measurements and detailed knowledge of the systematic errors provide results for geosynchronous satellites down to the 10 m level.

Next, the biases, constant and periodic terms, observed in the TDRSS data were applied to the DSCS-3/A1 data and orbit determination performed. Figure 5 shows the results of the abutment check for DSCS-3 for three cases: 1) no biases removed, 2) daily biases removed, and 3) daily and hourly biases removed. This was done to test the assumption was that the systematic errors are not spatially dependent and that the TDRS-5 systematic errors can be applied to other satellites during the same tracking interval. One sees that the continuity between the DSCS-3/A1 orbits does not improve and the solutions are much worse than the TDRS-5 cases. Closer inspection revealed that the differences are dominated by the along-track component.

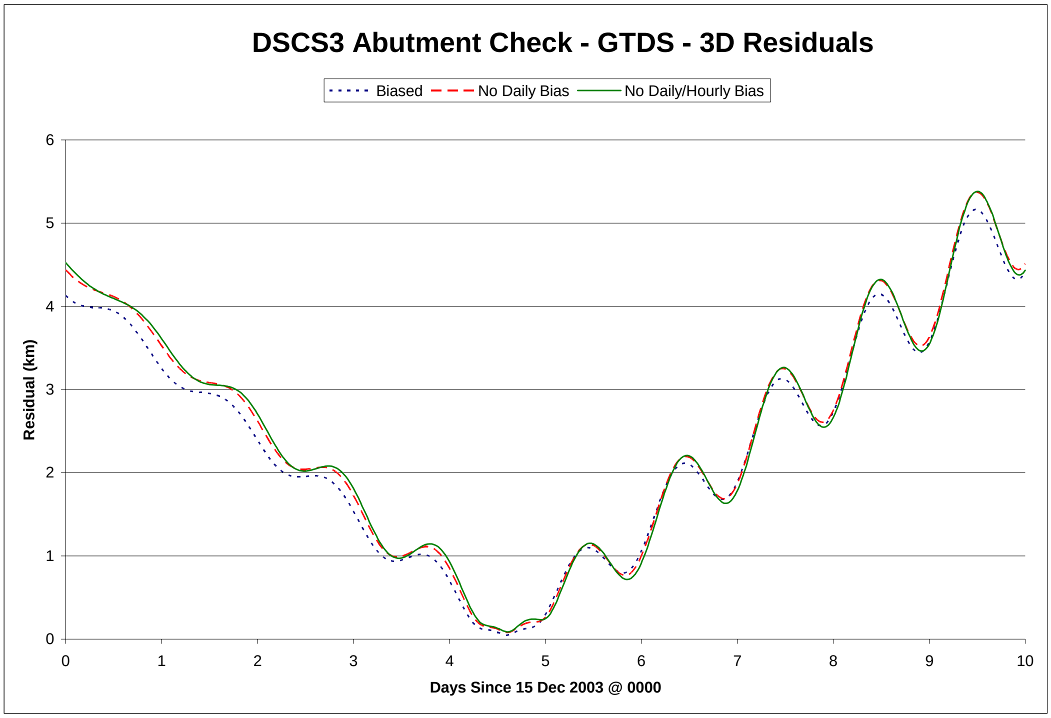

Figure 5 DSCS-3/A1 Abutment Check

The large along-track differences in the DSCS-3/A1 abutment check indicated that there were likely perturbation effects not being modeled in the orbit determination process. To counter this, a single, generalized along-track acceleration was estimated through the entire fit span. Including this along-track acceleration for TDRS-5 did not produce any appreciable improvement in orbital accuracy. For DSCS-3/A1, however, estimating an along-track acceleration resulted in a better solution. Figure 6 shows the improvement in the along-track direction when this parameter is estimated and Figure 7 shows the overall consistency improvement which is heavily driven by the along track improvement. In both figures, the TDRSS daily and periodic errors have been removed from the DSCS-3/A1 observations. The solutions, however, are still much worse than the TDRS-5 test case.

Figure 8 plots the abutment check for DSCS-3/A1 for the cases where no biases are removed from the data, daily TDRSS biases are removed from the data, and all of the TDRSS systematic errors are removed from the data. One can see the “unbiased” solutions have less agreement than the solutions using unaltered observations. Errors in both cases are still dominated by the along-track component but analysis revealed the “biased” case outperformed the “unbiased” case in all components, particularly in the cross-track direction where great improvement was seen in the TDRS-5 test case.

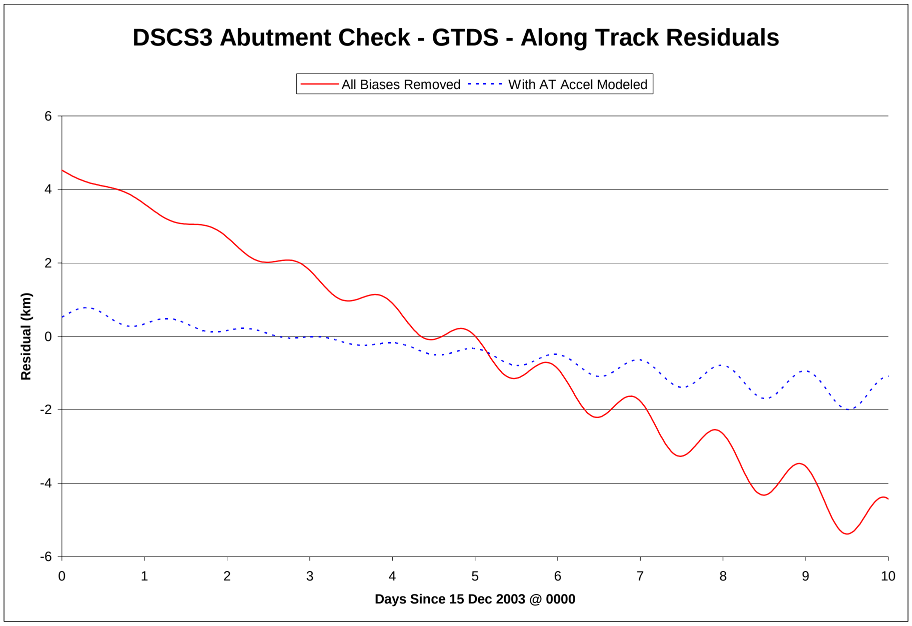

Figure 6 DSCS-3/A1 along-track abutment check with and without acceleration

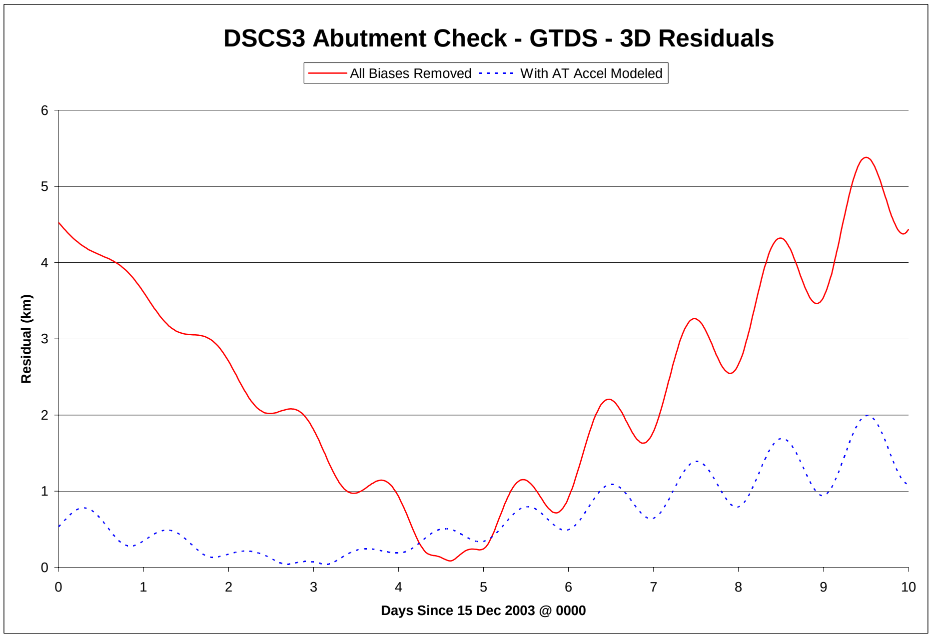

Figure 7 DSCS-3/A1 abutment check with and without acceleration

There were two likely reasons why the DSCS-3/A1 solutions were worse than the TDRS-5 test case: 1) the observation systematic errors have a spatial dependence so the TDRSS results can not be used to calibrate the DSCS-3/A1 data, or 2) there was not sufficient data in the short (~5 day) DSCS-3/A1 fit spans to generate an accurate solution. Additional analysis was performed to test these hypotheses.

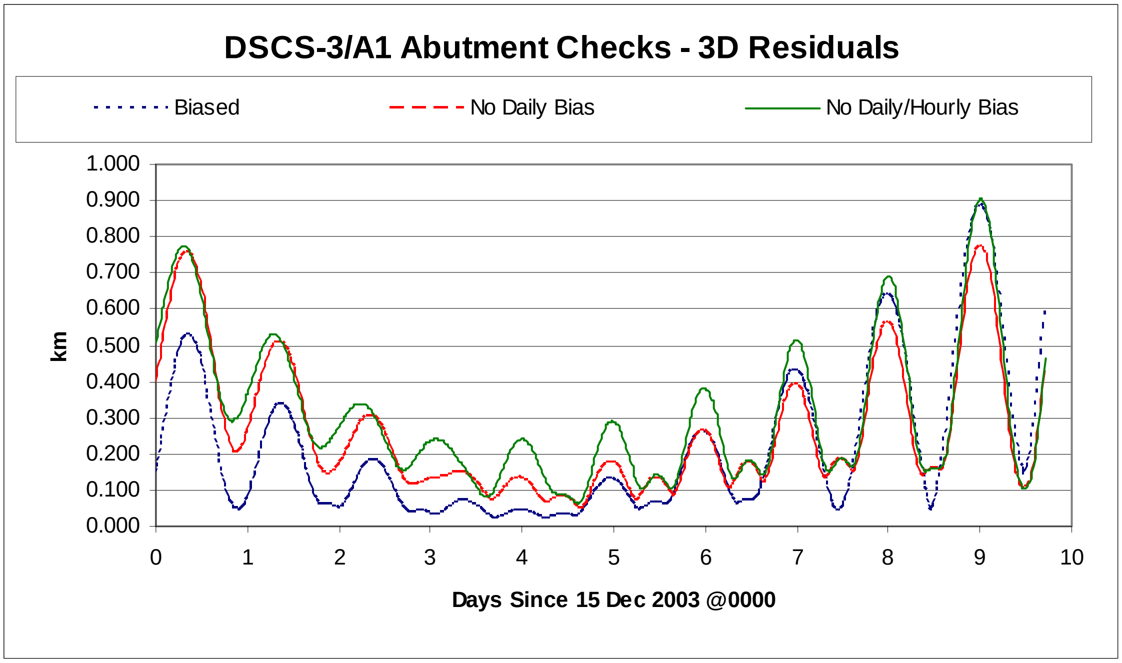

Figure 8 DSCS-3/A1 abutment check with and without TDRSS-based calibration

The next step was to perform an abutment analysis with the TDRS-5 data to determine if the shorter fit spans used in the abutment check provided useful information. As previously shown in Figures 2, 3, and 4, the overall accuracy of the orbit compared to the reference orbit improved drastically as the systematic errors were accounted for so once it was expected that the abutment check would show more continuity between the two fits for the corrected versus the uncorrected observations sets. Figure 9 shows the results of this test. The TDRS-5 results show some improvement in the abutment check but the orbits are considerably worse than the 10 day fits. The observation files for the results in Figure 9 were the same ones used in Figures 2-4. These results appear to support the hypothesis that there is insufficient data in the DSCS-3/A1 fits.

Additional analysis was performed to investigate is whether or not abutment checks are a good metric when qualifying the accuracy of orbit determination program runs. The shorter fit span solutions were then compared to the TDRS-5 reference orbit. The results are shown in Figure 10. As one can see, the abutment check is not terribly misleading in this case.

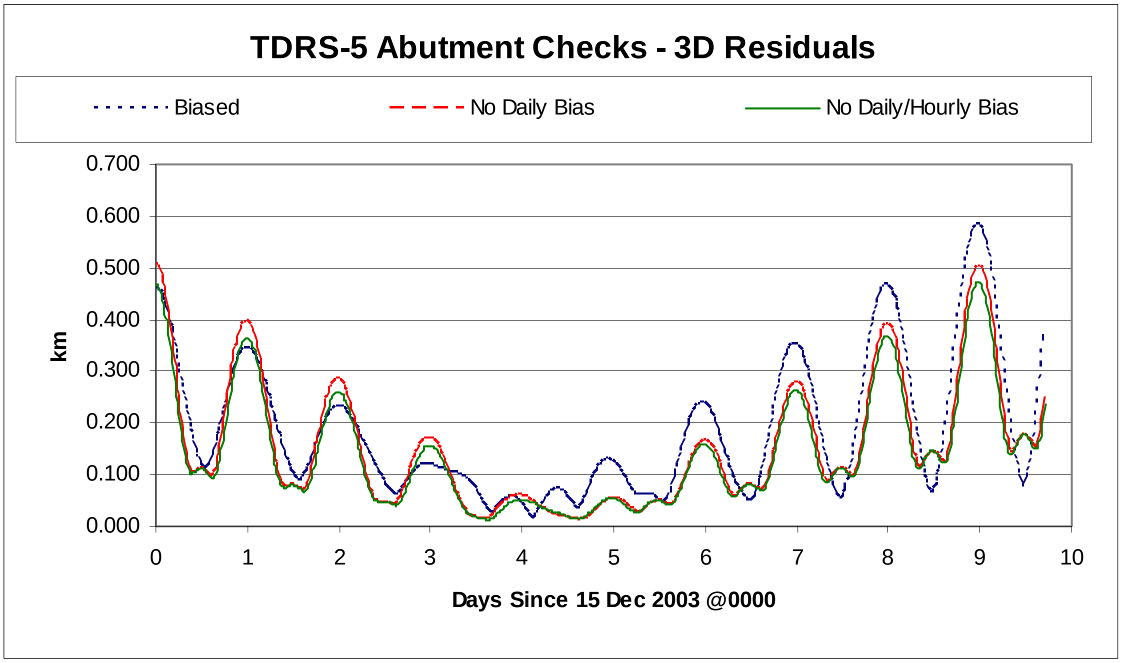

Figure 9 TDRS-5 Abutment Check

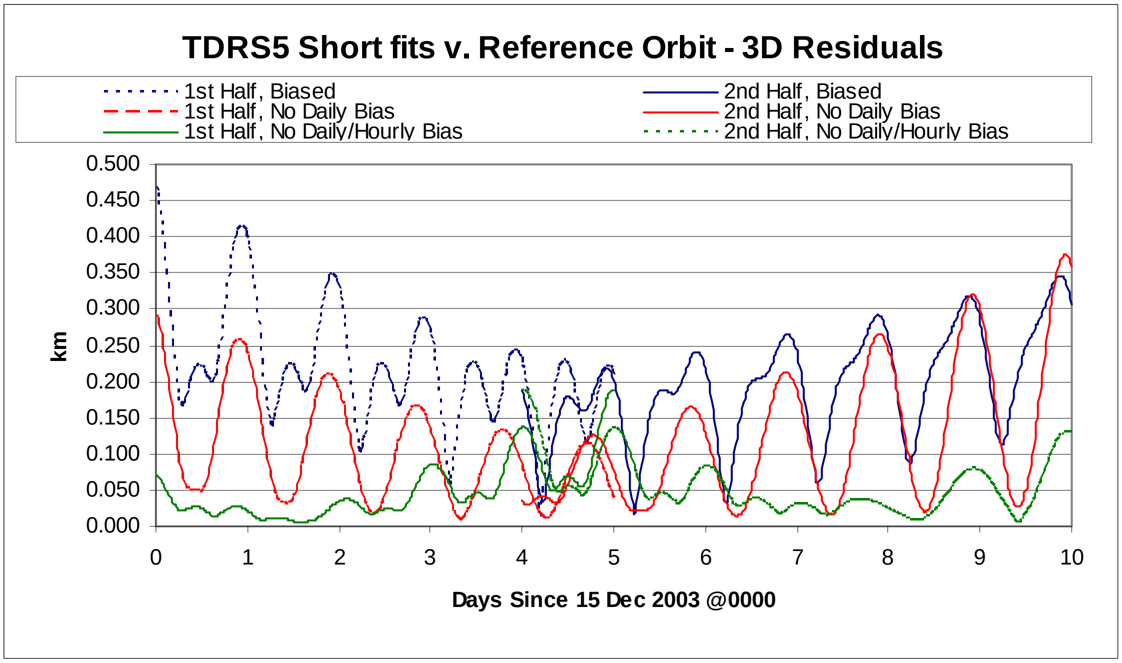

Figure 10 Short TDRS-5 fits compared to reference orbit

Since the DSCS-3/A1 abutment checks were inconclusive, inspection of orbit determination statistics for solutions incorporating all of the tracking data was performed. A ten day fit was found for each satellite for the period 15-24 December for two cases: 1) with no systematic errors removed and 2) with all TDRSS systematic errors removed. The results of this are below in Table 2.

Table 2 Orbit determination statistics for both satellites with and without corrections

	TDRS-5				DSCS-3		
	with Biases	w/o Biases	Delta		with Biases	w/o Biases	Delta
Rx (km)	0.0878	0.0812	0.0066		0.0329	0.0332	-0.0003
Ry (km)	0.0047	0.0044	0.0003		0.0236	0.0238	-0.0002
Rz (km)	0.0086	0.0080	0.0006		0.0036	0.0037	-0.0001
Vx (km/s)	2.75E-07	2.56E-07	1.90E-08		1.83E-05	1.85E-05	-2.00E-07
Vy (km/s)	4.71E-06	4.39E-06	3.20E-07		1.30E-05	1.31E-05	-1.00E-07
Vz (km/s)	5.33E-07	4.95E-07	3.80E-08		5.26E-06	5.30E-06	-4.00E-08
Cr	2.16E-02	2.02E-02	1.40E-03		4.55E-02	4.58E-02	-3.00E-04

When the biases are removed from the TDRS-5 observations the resulting standard deviations for the position and velocity vectors and the solar radiations pressure coefficient all improve slightly. When the same biases are removed from the DSCS-3/A1 observations all the resulting standard deviations are slightly worse. If the observation systematic errors were consistent for every satellite in the sky then one would expect the solutions to improve for both satellites as the systematic errors are removed from the observation set. The fact that this does not happen leads one to believe that the observation error models generated using the TDRSS data are not applicable to other satellites not in close proximity.

Following this line of thinking, another test was performed to allow one to see the biases throughout the data set. Since there was no truth or reference orbit for DSCS-3 the approach was a little different than previous analysis. The two unbiased observation sets were updated to account for the TDRSS biases and then a best-fit orbit was found for each of the four cases. The residuals between the observations and the model were found for both right ascension and declination. The declination data may be seen below in Figure 11.

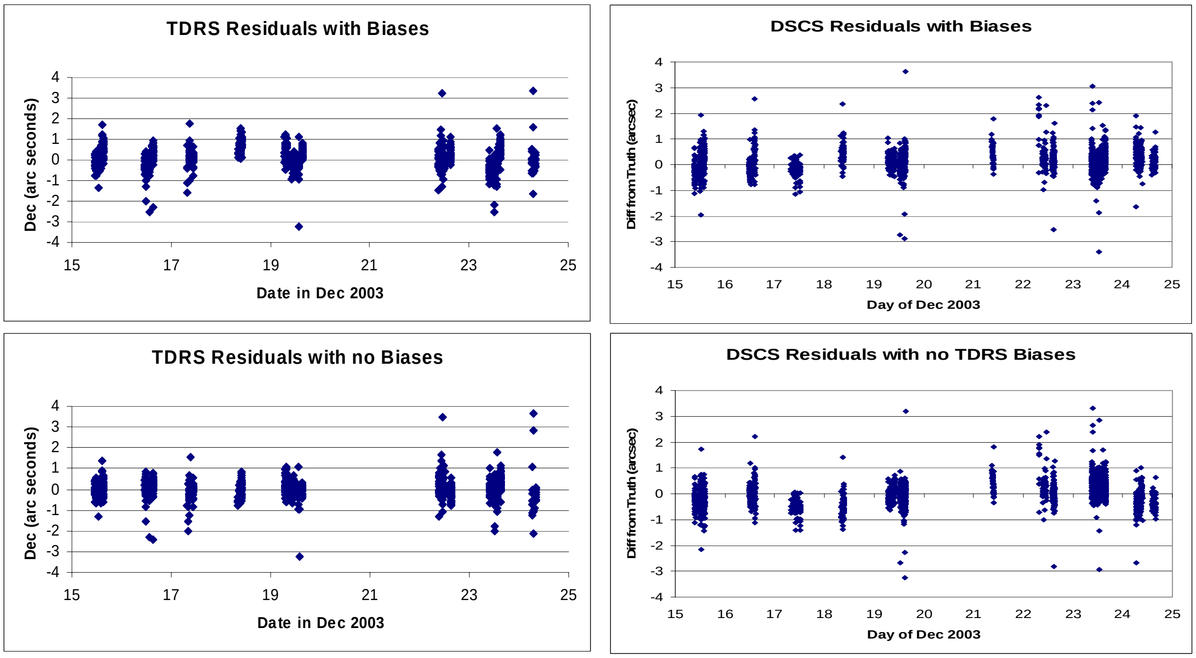

Figure 11 Declination Biases for TDRS-5 and DSCS-3/A1

Looking at the two TDRS plots one can see that residuals shift upward or downward nicely to align with the zero arc seconds line. The most significant change occurs on the 18th where approximately 0.75 arc seconds of bias is removed. Looking at the right two plots it is apparent that the declination biases for DSCS-3/A1 are not improved much and get worse for a number of days. Once again it appears that the observation biases also depend on something other than the day and the time.

CONCLUSIONS

It is difficult to draw conclusions from this work. From the TDRS-5 ten-day fits, it is clear that if the optical data has no systematic errors, one can produce high accuracy orbits using angles-only data. These results are in agreement with previous simulation work in this area. However, removing the systematic errors from the optical observation sets used in this research has proven to be a challenge. It was hoped that the optical data could be calibrated using a satellite with a known reference orbit, such as TDRSS, but the results presented here indicate that the observation error models may not be consistent between satellites.

During the course of this research, the importance of adequate force modeling was observed. For the DSCS-3/A1 case, neglecting to include a generalized along-track acceleration in the estimation state produced far worse errors than the errors in the observation set. No matter how accurate the observations, they are meaningless unless the orbit dynamics support that accuracy.

Additionally, the use of abutment or consistency checks was reviewed. Consistency checks are widely used and are an accepted way to infer accuracy; however, the results here showed that it's terribly useful to anchor the results if possible to ensure that the consistency checks are not misleading.

The easiest conclusion to draw from this work is that more work is needed. For the HANDS program, the priority is on trying to understand the source of the systematic errors in the optical data and hopefully correct them. Some of the orbit determination results in this work are not well understood and must be rechecked and verified to ensure erroneous results have not been reported. The results may indicate that additional work is needed on observation error modeling. Finally, since some of these results were not observed in previous analysis, additional data collection and review is required.

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